LA-5963

UC-46
Reporting Date: April 1975
Issued: July 1975

Reflector-Moderated Critical Assemblies

by

Hugh C. Paxton
George A. Jarvis
Cleo C. Byers

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87545

UNITED STATES
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
CONTRACT W-7405-ENG. 36

Printed in the United States of America. Available from
National Technical Information Service
U S Department of Commerce
5285 Port Royal Road
Springfield, VA 22151
Price: Printed Copy $4.00 Microfiche $2.25

REFLECTOR-MODERATED CRITICAL ASSEMBLIES

by

Hugh C. Paxton
George A. Jarvis
Cleo C. Byers

ABSTRACT

Experiments with reflector-moderated critical assemblies were part of the Rover Program at the Los Alamos Scientific Laboratory (LASL). These assemblies were characterized by thick D_2O or beryllium reflectors surrounding large cavities that contained highly enriched uranium at low average densities. Because interest in this type of system has been revived by LASL Plasma Cavity Assembly studies, we provide more detailed descriptions of the early assemblies than had been available in the unclassified literature.

SCOPE

As a low-priority adjunct of the Rover program, experiments with D_2O-reflected cavity-type critical assemblies and beryllium-reflected subcritical assemblies were done between 1959 and 1964. The fissile materials used were U(93) foil and U(93)-loaded Rover fuel elements. This account supplements incomplete, unclassified reports of results (Refs. 1 and 2) and emphasizes critical or supercritical models that are appropriate for two-dimensional calculations. These experimental models serve as check points for recent transport calculations that apply to UF_6-gas-fueled systems of interest to the National Aeronautics and Space Administration (NASA).[3,4]

Background. Applications of gas-core reactors suggested as early as 1957 included direct electric conversion[5] followed by rocket propulsion.[6] Beginning in 1967, critical experiments directed toward propulsion systems were conducted at the National Reactor Testing Station by the General Electric Company under NASA sponsorship.[7,8] D_2O-reflected cavity assemblies were fueled in some cases by distributed enriched-uranium foils and in other cases by gaseous UF_6. In the more detailed mockups, hydrogenous material between the core and reflector represented gaseous-hydrogen propellant. The only other experience with UF_6 as a reactor fuel began as early as 1957 in the USSR.[9] There, a heterogeneous core with beryllium moderator was reflected by graphite. The power, 1.5 kW, was sufficient to demonstrate the effectiveness of ClF_3 in preventing decomposition of the UF_6 by fission products and other ionizing radiation.

Since 1955 extensive parametric studies of cavity reactors have used one-dimensional diffusion and transport techniques.[2,4,8,10,11] At the Los Alamos Scientific Laboratory (LASL) and the Rand Corporation, critical masses were computed as functions of spherical cavity size and thickness of beryllium, D_2O, and carbon reflectors. In the meantime, two-dimensional diffusion calculations at NASA's Lewis Research Center, Douglas Aircraft Company, and United Aircraft Research Laboratories were applied to specific rocket-reactor models.[12-14]

Objectives. Like the early computational surveys, the LASL experiments were aimed at establishing general characteristics of simple systems instead of providing engineering data. In fact the early critical descriptions[1] now seem oversimplified in view of the detail that modern computing machines and codes can handle. Consequently, one of our purposes is to provide the more complete, precise descriptions that are compatible with present two-dimensional computing techniques. But because not all detailed critical specifications can now be reconstructed reliably, there is no attempt to be comprehensive. Among the better specifications, we have further selected those which provide a reasonably varied set of checkpoints for calculation. Another purpose, of course, is to compare the resulting set of specifications with the outcome of modern two-dimensional computation.

ASSEMBLIES WITH D_2O REFLECTOR

Reflector. The heavy-water setup, illustrated in Figs. 1 and 2, was basically an ~490-mm-thick D_2O reflector surrounding a near-equilateral cylindrical cavity (~1040 mm) that contained the fissile material. The annular reflector tank and upper and lower plug tanks were of type 6061 aluminum, mostly 3.2- or 4.8-mm-thick next to the cavity and thicker on the outside. A central opening (128-mm radius) in the top of the lower plug tank allowed inserts to carry detectors into the reflector or to open a cylindrical channel through the D_2O. Normally, this opening was covered by a 3.2-mm-thick aluminum plate (154-mm radius).

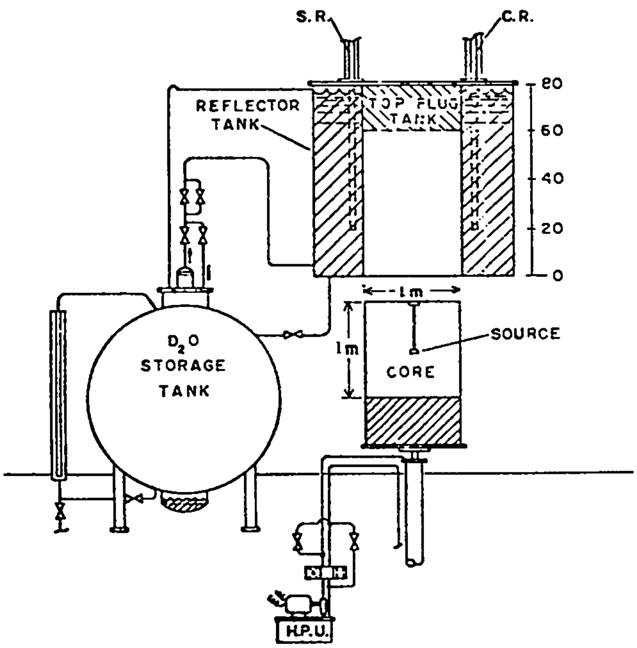

Fig. 1.
Heavy-water reflector for cavity assemblies.

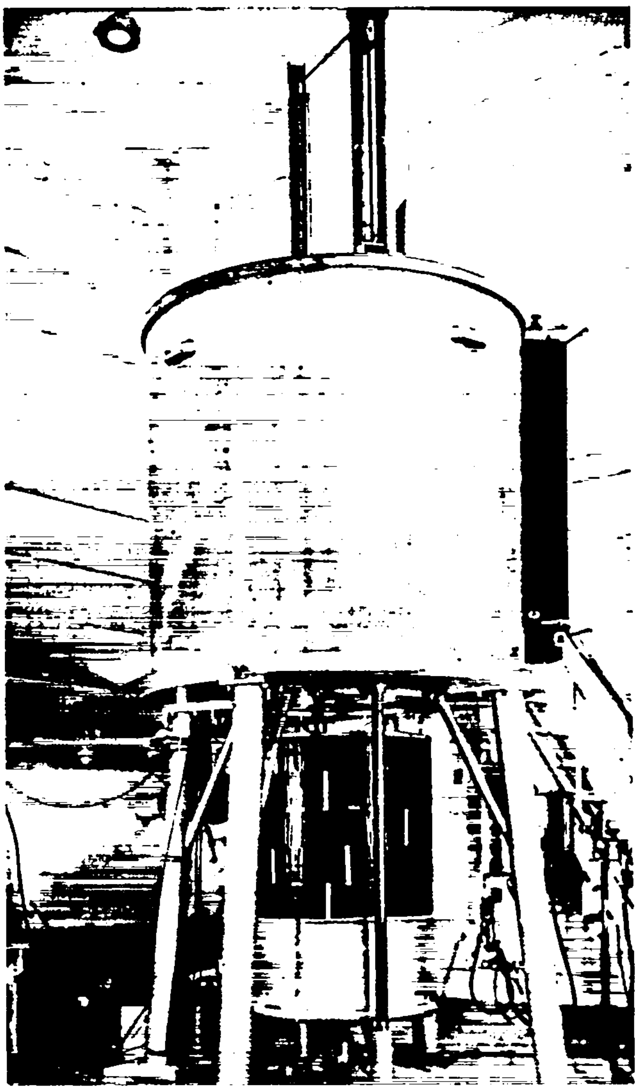

Fig. 2.
Heavy-water assembly with retracted cavity liner of enriched-uranium foil.

The lower plug tank and core material, on a hydraulic lift, were withdrawn from the closed position whenever the assembly was not in operation. A sheathed-cadmium control rod and similar safety rod extended down into drywells within the annular tank (displacing 3.2 liters of D_2O at a radius of 578 mm). The H_2O impurity in the heavy water was 0.8 wt%.

Table I describes the reflector system in r,z coordinates. The volumes of off-axis drywells for control and safety rods are distributed as annuli at the correct average radius; otherwise symmetry was built in. Except where volume percent is specified, the listed materials fill zones at full density (2.70 g/mℓ

TABLE I

D_2O-REFLECTOR COORDINATES

z (mm)	r (mm)	Material
0-25.40	0-1027.81	6061 Al
25.40-508.00	0-515.53	D_2O (99.2 wt%)
25.40-508.00	515.53-518.71	6061 Al
508.00-514.35	0-128.27	D_2O
508.00-514.35	128.27-153.67	6061 Al
508.00-514.35	153.67-515.53	D_2O
508.00-514.35	515.53-518.71	6061 Al
514.35-517.52	128.27-153.67	6061 Al
514.35-517.52	515.53-518.71	6061 Al
517.52-520.70	128.27-518.71	6061 Al
520.70-523.88	0-153.67	6061 Al
523.88-1555.24	0-519.81	core
1555.24-1560.00	0-518.71	6061 Al
1560.00-2047.37	0-515.53	D_2O
1560.00-2047.37	515.53-518.71	6061 Al
2047.37-2050.54	515.53-518.71	6061 Al
2050.54-2063.24	0-1027.81	6061 Al
2063.24-2075.94	0-546.10	6061 Al
25.40-509.07	519.81-522.99	6061 Al
25.40-509.07	522.99-1015.11	D_2O
25.40-509.07	1015.11-1027.81	6061 Al
509.07-763.07	519.81-522.99	6061 Al
509.07-763.07	522.99-577.69	D_2O
509.07-763.07	577.69-578.00	16.6 vol% 1100 Al[a]
509.07-763.07	578.00-1015.11	D_2O
509.07-763.07	1015.11-1027.81	6061 Al
763.07-2050.54	519.81-522.99	6061 Al
763.07-2050.54	522.99-577.54	D_2O
763.07-2050.54	577.54-578.17	16.6 vol% 1100 Al
763.07-2050.54	578.17-1015.11	D_2O
763.07-2050.54	1015.11-1027.81	6061 Al

[a]Control, safety drywell volumes distributed at r = 577.85 mm.

for 6061 aluminum, 2.71 g/mℓ for 1100 aluminum, 1.104 g/mℓ for 99.2 wt% D_2O); unlisted zones are empty.

For one series of measurements,[1] drywells extending into the lower plug tank established axial openings of several sizes through the reflector. These simulated, somewhat, the effect of a rocket nozzle. Modified r,z coordinates for the lower plug tank with the largest insert, 127-mm-radius opening, are given in Table II. For consistency with a zone of Table I, the material in a 6.4-mm-thick flange on the insert is spread over a 3.2-mm thickness of increased radius.

Foil-Liner Core. The core that can be described most precisely in two dimensions consisted of 0.076-mm-thick foil that essentially lined the cavity. An aluminum drum (1.6-mm-thick wall and cover, with reinforcing rings) supported the lateral and top foil about 7 mm from the cavity surfaces. The bottom foil rested on the cover plate of the lower plug tank.

TABLE II

COORDINATES OF 254-MM-DIAM NOZZLE MOCKUP[a]

z (mm)	r (mm)	Material
0-25.40	0-1027.81	6061 Al
25.40-26.67	0-515.53	D_2O
25.40-26.67	515.53-518.71	6061 Al
26.67-29.84	0-127.00	6061 Al
26.67-29.84	127.00-515.53	D_2O
26.67-29.84	515.53-518.71	6061 Al
29.84-508.00	123.82-127.00	6061 Al
29.84-508.00	127.00-515.53	D_2O
29.84-508.00	515.53-518.71	6061 Al
508.00-514.35	123.82-153.67	6061 Al
508.00-514.35	153.67-515.53	D_2O
508.00-514.35	515.53-518.71	6061 Al
514.35-517.52	123.82-153.67	6061 Al
514.35-517.52	515.53-518.71	6061 Al
517.52-520.70	123.82-518.71	6061 Al
520.70-523.88	123.82-178.60[b]	6061 Al

[a]Modification of lower plug-tank coordinates.

[b]Enlarged to equivalent volume of double-thickness flange.

The r,z coordinates describing this core appear in Table III.

With all foil in place, and with the unperturbed reflector (Table I), the system was critical when the control rod was inserted and the safety rod was incompletely withdrawn to a standard operating position. Correcting for full withdrawal of both rods, the excess reactivity was 2.58$ (Keepin-Wimett units).

A 254-mm-diam opening through the lower reflector, the modification of Table II, dropped the reactivity 1.80$. Thus, with the core of Table III and perturbed reflector, the excess reactivity was 0.78$ after correction for rod withdrawal.

Rover Fuel Cores. Reference 1 describes many critical distributions of Rover fuel elements in the unperturbed D_2O system cavity (Table I). The hexagonal elements (19.0 mm across flats, with nineteen 2.5-mm-diam flow channels) were shortened to 991 mm from an original 1321-mm length. On the average, each element contained 89.9 g U(93.1) and 383.3 g carbon, and was wrapped with 7.0 g aluminum foil to control contamination. As shown in Fig. 3, the elements were supported by two

TABLE III

FOIL-LINER CORE COORDINATES[a]

z (mm)	r (mm)	Material
520.70-523.88	510.76-517.12	6061 Al
$523.88\text{-}523.95_{75}$	0-500.97	1149.15 g U(93.1)[b]
$523.88\text{-}523.95_{75}$	510.76-517.12	6061 Al
523.96-533.40	510.76-517.12	6061 Al
533.40-1534.60	510.76-512.36	6061 Al
533.40-1534.60	$512.36\text{-}512.43_{75}$	4697.51 g U(93.1)[b]
1534.60-1547.30	510.76-517.12	6061 Al
1547.30-1548.89	0-512.36	6061 Al
$1548.89\text{-}1548.96_{75}$	0-510.93	1195.27 g U(93.1)[b]

[a]2.58$ supercritical with standard reflector; effect of 254-mm-diam nozzle mockup −1.80$.

[b]Total 7042 g U(93.1); critical mass 6400 ± 50 g with uniform foil thickness.

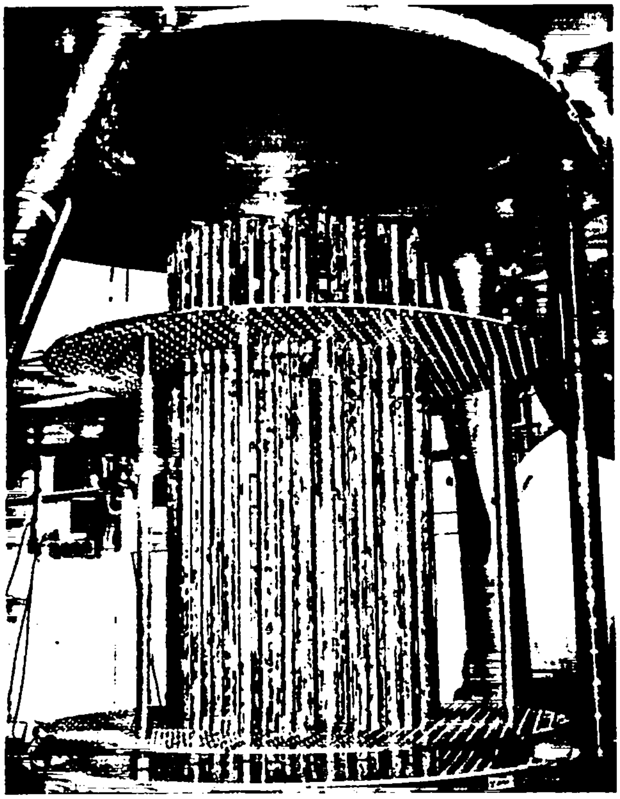

Fig. 3.
Rover fuel elements in cavity of D_2O assembly. Aluminum foil on each element reduces contamination.

aluminum templates separated with three aluminum rods and secured by nine steel nuts. The triangular pattern of 22.2-mm-diam holes with a pitch of 28.6 mm (1.125 in.) is shown in Fig. 4.

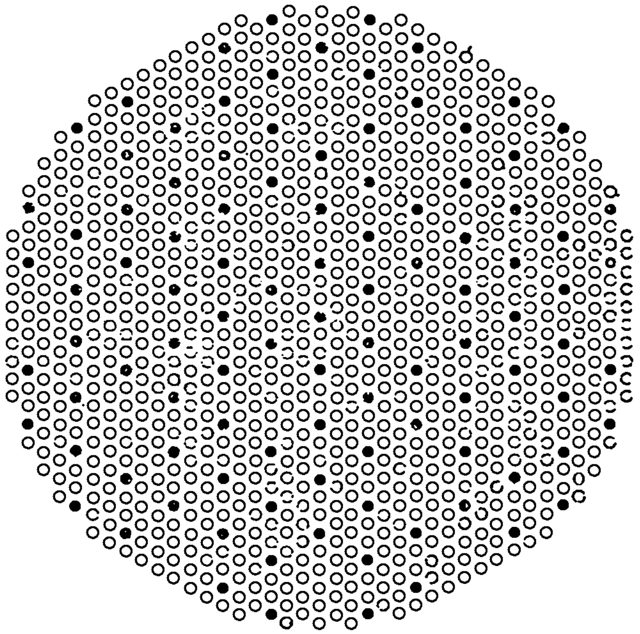

Fig. 4.
Uniform distribution of Rover elements or foil tubes (dark circles) in D_2O assembly. The neutron source is located near the center.

Of the various critical fuel-element patterns, only three had control-rod calibrations in reactivity units and numbers of elements. Only in these cases could excess reactivities be assigned to perturbation-free systems with the actual patterns measured. Thus, they are better defined in terms of volumes associated with fuel, and have been selected for two-dimensional models. For these models, of course, some uncertainty is introduced because fuel must be smeared throughout its associated volume. Assigned excess reactivities include effects of withdrawing control and safety rods, and of removing the three aluminum spacer rods and nine nuts, which do not fit a two-dimensional model. All corrections were established experimentally.

With a nearly uniform loading, similar to that of Fig. 4, criticality was attained with 98 elements. Corrections of 0.75$ for withdrawal of control and safety rods, and 0.50$ to compensate for the aluminum spacer rods and steel nuts, lead to a total excess reactivity of 1.25$. These quantities, and the reactivity contribution of an average fuel element, appear in the first column of Table IV. The masses associated with 98 elements are 8810 g U(93.1), 37560 g carbon, and 686 g aluminum foil wrapper. For the r,z description of Table V, these masses are distributed uniformly throughout the volume of cavity extending 991 mm above a 14795 g aluminum

TABLE IV

REACTIVITY EFFECTS IN ROVER ELEMENT CORES

	Uniform Distribution	Single Ring	Close-packed Cluster
Number of elements	98	94	285
Reactivity per element ($)	0.29	0.30	0.064
Control and safety correction ($)	0.75	0.97	0.49
Spacer and nut correction ($)	0.50	0.37	0.37
Excess reactivity after correction ($)	1.25	1.34	0.86

TABLE V

COORDINATES OF CORE WITH UNIFORMLY DISTRIBUTED ROVER ELEMENTS[a]

z (mm)	r (mm)	Material
523.88-530.23	0-503.24	6061 Al
530.23-581.03	0-519.81	451.82 g U(93.1),[b] 1926 g C, and 35 g Al
581.03-587.38	0-519.81	56.48 g U(93.1),[b] 241 g C, and 5960 g 6061 Al[c]
587.38-1279.53	0-519.81	6156.12 g U(93.1),[b] 26247 g C, and 479 g Al
1279.53-1285.88	0-519.81	56.48 g U(93.1),[b] 241 g C, and 5959 g 6061 Al[c]
1285.88-1520.83	0-519.81	2089.69 g U(93.1),[b] 8910 g C, and 162 g Al

[a] 1.25$ supercritical with standard reflector.

[b] Total 8810 g U.

[c] Aluminum actually extends to r = 503.24 mm.

base plate. The lower and upper aluminum support plates, 5956 and 5955 g, respectively, are also included in the model.

The effect of elevating the D_2O temperature was measured for a near-uniformly loaded core with 122 elements. Relative to a reflector temperature of 18.3°C, a reactivity loss of 1.30$ was observed with D_2O temperatures of 60.0°C in the annular tank, 31.1°C in the upper plug tank, and 20.6°C in the lower plug tank.

Another simple loading, consisting of a single ring of elements as close to the cavity wall as possible, is illustrated by Fig. 5. For the actual critical number of elements, 94, corrections listed in the second column of Table IV lead to 1.34$ excess reactivity. Fuel masses are 8451 g U(93.1), 36030 g carbon, and 658 g aluminum wrapper. Because this ring of elements is a discontinuous target for neutrons

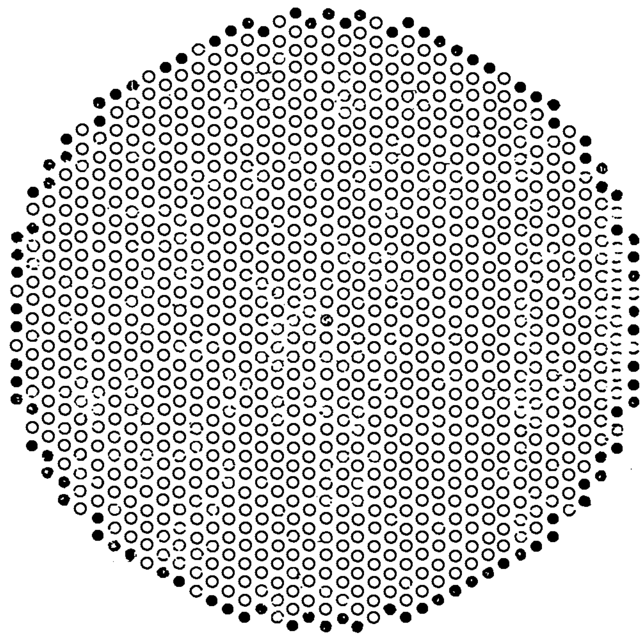

Fig. 5.
Peripheral distribution of Rover elements or foil tubes (dark circles) in D_2O assembly. S represents the neutron source location.

returning to the cavity, any simple two-dimensional model is questionable. Perhaps the best reason for the r,z description of Table VI is to show the extent to which it is defective, by comparing two-dimensional calculations and experiments. Somewhat arbitrarily, the annular fuel zone in this model is assigned the matrix cell volume per element at the average radius of elements in the ring.

The other selected pattern of elements, close-packed about the axis, is shown in Fig. 6. Corrections giving excess reactivity are in the last column of Table IV. The 285 elements have masses of 25622 g U(93.1), 109240 g carbon, and 1995 g aluminum foil. The corresponding r,z model of Table VII is straightforward and like the model for uniformly distributed elements, is expected to introduce little calculational distortion.

Metal-Tube Cores. Cores similar to those with Rover elements were made of tubes formed from 0.076-mm-thick U(93.2) foil. The tubes, 22.2-mm diam and 1003 mm long, each weighed about 97 g. They were supported by the same structure used for the Rover fuel. From a number of critical patterns, the geometry of only two can be reconstructed reasonably well, and in no case was the control rod calibrated in terms of reactivity units. Thus there is no reliable means of assigning excess reactivity to an

TABLE VI

COORDINATES OF CORE WITH SINGLE RING OF ROVER ELEMENTS[a]

z (mm)	r (mm)	Material
523.88-530.23	0-503.24	6061 Al
530.23-581.03	466.12-488.28	433.35 g U(93.1),[b] 1847 g C, and 139 g Al
581.03-587.38	0-466.12	5110 g 6061 Al
581.03-587.38	466.12-488.28	54.17 g U(93.1),[b] 231 g C, and 501 g 6061 Al
581.03-587.38	488.28-503.24	349 g 6061 Al
587.38-1279.53	466.12-488.28	5904.41 g U(93.1),[b] 25174 g C, and 438 g Al
1279.53-1285.88	0-466.12	5109 g 6061 Al
1279.53-1285.88	466.12-488.28	54.17 g U(93.1),[b] 231 g C, and 501 g 6061 Al
1279.53-1285.88	488.28-503.24	349 g 6061 Al
1285.88-1520.83	466.12-488.28	2004.25 g U(93.1),[b] 8545 g C, and 157 g Al

[a] 1.34$ supercritical with standard reflector.
[b] Total 8451 g U.

TABLE VII

COORDINATES OF CORE WITH ROVER ELEMENTS CLOSE-PACKED ON AXIS[a]

z (mm)	r (mm)	Material
523.88-530.23	0-503.24	6061 Al
530.23-581.03	0-253.26	1313.91 g U(93.1), 5601 g C, and 103 g Al
581.03-587.38	0-253.26	164.24 g U(93.1), 701 g C, and 1521 g 6061 Al
581.03-587.38	253.26-503.24	4448 g 6061 Al
587.38-1279.53	0-253.26	17902.05 g U(93.1), 76328 g C, and 1394 g Al
1279.53-1285.88	0-253.26	164.24 g U(93.1), 701 g C, and 1521 g 6061 Al
1279.53-1285.88	253.26-503.24	4447 g 6061 Al
1285.88-1520.83	0-253.26	6076.84 g U(93.1), 25910 g C, and 473 g Al

[a] 0.86$ supercritical with standard reflector.

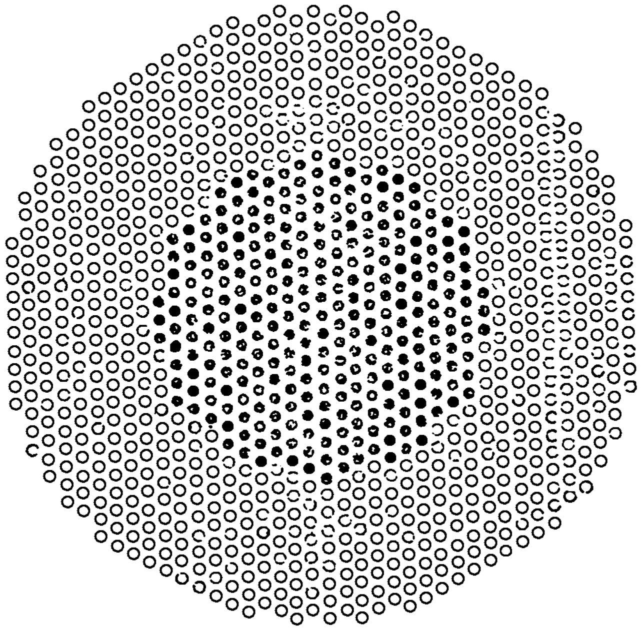

Fig. 6.
Axial cluster of Rover elements or foil tubes (dark circles) in D_2O assembly. The neutron source is located near the center.

as-measured configuration. Instead, experimentally based corrections adjust the critical number of fuel tubes for complete withdrawal of control and safety rods and for removal of the three aluminum spacer rods and nine nuts.

For one of the selected patterns, the near-uniform distribution of Fig. 4, criticality was attained with 96 fuel tubes. Complete withdrawal of control and safety rods would be compensated by the removal of 3.43 tubes of average effectiveness, and another 1.52 tubes were equivalent in effect to the three aluminum rods and nine nuts. The critical number of tubes after correction, 91.05, had a total weight of 8790 g U(93.2). The resulting critical two-dimensional model of Table VIII has the fuel smeared throughout a 1003-mm height in the cavity.

The other pattern was with tubes close-packed on the axis, as shown in Fig. 6. In this case, the observed critical number of fuel tubes was 264. Corrections were 4.49 exterior tubes for complete withdrawal of control and safety rods, and 5.34 to compensate for the aluminum rods and steel nuts. The resulting idealized critical number, 254.17, containing a total mass of 24324 g U(93.2), is incorporated in the r,z description of Table IX.

Descriptions of these foil-tube assemblies suffer from the difficulty of defining a tube to serve as a unit for correction—the proper weighted-average tube in the uniform distribution and the average external tube in the close-packed array. This could introduce an $\sim$1% uncertainty in mass (a significant fraction of the 4-5% correction). Nevertheless, the tube models may be useful because of simple fuel composition.

TABLE VIII

CRITICAL COORDINATES OF CORE WITH UNIFORMLY DISTRIBUTED FOIL TUBES

z (mm)	r (mm)	Material
523.88-530.23	0-503.24	6061 Al
530.23-581.03	0-519.81	445.06 g U(93.2)
581.03-587.38	0-519.81	55.63 g U(93.2) and 5956 g 6061 Al[a]
587.38-1279.53	0-519.81	6063.94 g U(93.2)
1279.53-1285.88	0-519.81	55.63 g U(93.2) and 5955 g 6061 Al[a]
1285.88-1533.53	0-519.81	2169.67 g U(93.2)

[a]The aluminum actually extends to r = 503.24 mm.

ASSEMBLIES WITH BERYLLIUM REFLECTORS

Reflectors. Our beryllium-reflected cavity assemblies were improvised from available materials and equipment. As shown in Fig. 7, they were mounted on an assembly machine that was normally used for Rover reactor mockups.

Two versions of the stationary part of the reflector, shown in Fig. 8, had the same re-entrant cylindrical opening (1168 mm deep) but differing lateral thicknesses (356 mm and 470 mm). Nesting beryllium rings (to 389-mm i.d. by 648-mm o.d.) surrounded the upper 762 mm of the cavity and had a density of ~1.82 g/mℓ. Elsewhere, the stationary reflector was an assemblage of parallelepipeds, wedges, and annular segments with the somewhat reduced density of ~1.72 g/mℓ. The closure plug, on a hydraulic lift, consisted of a uniform stack of beryllium plates (381 mm high by 387-mm diam), also at the higher density. Like the D_2O system, core

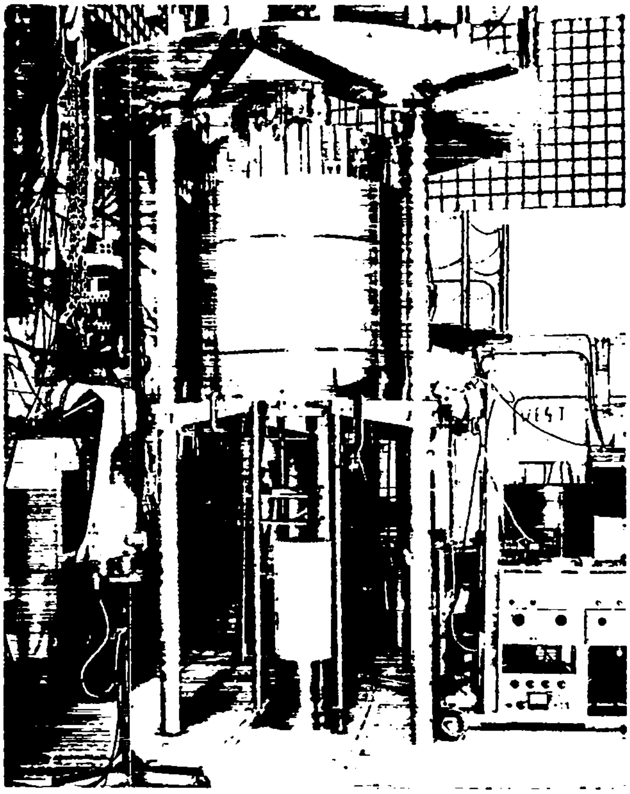

Fig. 7.
Beryllium-reflected assembly with retracted container for Rover fuel elements.

TABLE IX

CRITICAL COORDINATES OF CORE WITH FOIL TUBES CLOSE-PACKED ON AXIS

z (mm)	r (mm)	Material
523.88-530.23	0-503.24	6061 Al
530.23-581.03	0-239.19	1231.60 g U(93.2)
581.03-587.38	0-239.19	153.95 g U(93.2) and 1346 g 6061 Al
581.03-587.38	239.19-503.24	4610 g 6061 Al
587.38-1279.53	0-239.19	16780.55 g U(93.2)
1279.53-1285.88	0-239.19	153.95 g U(93.2) and 1346 g 6061 Al
1279.53-1285.88	239.19-503.24	4609 g 6061 Al
1285.88-1533.53	0-239.19	6004.05 g U(93.2)

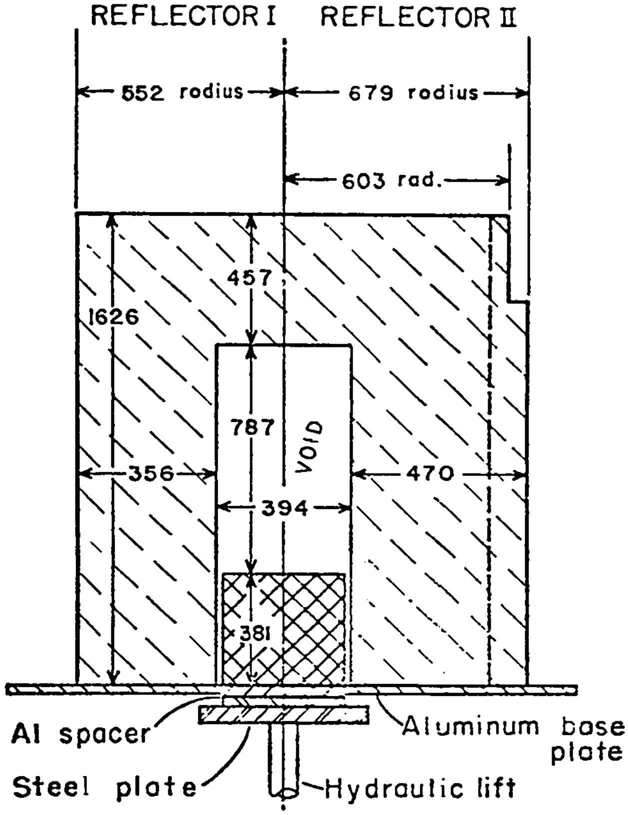

Fig. 8.
Thin and thick beryllium reflectors for cavity assemblies. (Dimensions in millimeters.)

material was carried on the closure plug, both raised into operating position by the hydraulic lift.

The thinner and thicker reflectors are described in r, z coordinates in Tables X and XI. There is neither a control nor a safety rod to complicate the geometry. All beryllium is Brush grade S-200-C or the equivalent. A 1.6-mm-thick aluminum cylinder and 9.5-mm-thick base plate, which held the fuel, are included in these descriptions.

Local restrictions prevented our attaining criticality without control and safety rods. Instead, reciprocal neutron multiplication as a function of core mass was extrapolated to criticality from a multiplication of ~100. The maximum masses attained ranged from 91 to 98% of the deduced critical values, thereby implying extrapolation uncertainties of 1/2 to 2 1/2%.

Foil-Liner Cores. Cores that consisted of foil lining the cavity are not as cleanly defined as the similar core in the larger D_2O system. Instead of uniformly thin foil on all surfaces, strips of 0.76-mm-thick U(93.1) foil were wound into the supporting cylinder

TABLE X

COORDINATES OF THIN BERYLLIUM REFLECTOR

z (mm)	r (mm)	Material[a]
0-31.75	0-193.68	6061 Al
31.75-50.80	0-552.45	6061 Al
50.80-431.80	0-193.68	Be, 1.821 g/ml
50.80-431.80	196.85-552.45	Be, 1.729 g/ml
431.80-441.32	0-192.09	6061 Al
431.80-441.32	196.85-552.45	Be, 1.729 g/ml
441.32-1219.20	0-190.50	cavity
441.32-457.20	190.50-192.09	6061 Al
441.32-457.20	196.85-552.45	Be, 1.729 g/ml
457.20-1193.80	190.50-192.09	6061 Al
457.20-1193.80	196.85-323.85	Be, 1.821 g/ml
457.20-1193.80	323.85-552.45	Be, 1.729 g/ml
1193.80-1219.20	196.85-323.85	Be, 1.821 g/ml
1193.80-1219.20	323.85-552.45	Be, 1.729 g/ml
1219.20-1676.40	0-552.45	Be, 1.729 g/ml

[a]The beryllium total is 2546 kg; the density distribution is approximate.

TABLE XI

COORDINATES OF THICK BERYLLIUM REFLECTOR

z (mm)	r (mm)	Material[a]
0-31.75	0-193.68	6061 Al
31.75-50.80	0-679.45	6061 Al
50.80-431.80	0-193.68	Be, 1.821 g/ml
50.80-431.80	196.85-552.45	Be, 1.729 g/ml
50.80-431.80	552.45-679.45	Be, 1.664 g/ml
431.80-441.32	0-192.09	6061 Al
431.80-441.32	196.85-552.45	Be, 1.729 g/ml
431.80-441.32	552.45-679.45	Be, 1.664 g/ml
441.32-1219.20	0-190.50	cavity
441.32-457.20	190.50-192.09	6061 Al
441.32-457.20	196.85-552.45	Be, 1.729 g/ml
441.32-457.20	552.45-679.45	Be, 1.664 g/ml
457.20-1193.80	190.50-192.09	6061 Al
457.20-1193.80	196.85-323.85	Be, 1.821 g/ml
457.20-1193.80	323.85-552.45	Be, 1.729 g/ml
457.20-1193.80	552.45-679.45	Be, 1.664 g/ml
1193.80-1219.20	196.85-323.85	Be, 1.821 g/ml
1193.80-1219.20	323.85-552.45	Be, 1.729 g/ml
1193.80-1219.20	552.45-679.45	Be, 1.664 g/ml
1219.20-1371.60	0-552.45	Be, 1.729 g/ml
1219.20-1371.60	552.45-679.45	Be, 1.664 g/ml
1371.60-1676.40	0-552.45	Be, 1.729 g/ml
1371.60-1676.40	552.45-603.25	Be, 1.664 g/ml

[a]The beryllium total is 3720 kg, distributed as in the thin reflector to a radius of 552 mm and at a lower average density beyond.

to give an average lateral thickness, and squares of foil were distributed over the base plate and over a 1.6-mm aluminum cover plate at different average thicknesses.

With the thin beryllium reflector of Table X, there was 859 g U(93.1) over the bottom (averaging 0.40

mm), 451 g on the top (0.21 mm), and an extrapolated critical mass of 10695 g (0.63 mm) on the lateral surface where final additions occurred. Table XII describes this core with averaged fuel thicknesses. In this case, neutron multiplication measurements extended to only 90.7% of the extrapolated critical mass.

The description of a similar core in the thick reflector (Table XI) appears in Table XIII. This core consisted of 429 g U(93.1) over the bottom (averaging 0.20 mm), another 429 g on the top, and an extrapolated 7644 g on the cylinder wall (0.45 mm). Here, the mass attained was 94.5% of the critical value.

Rover Fuel Cores. Several beryllium-reflected assemblies used an early type of Rover fuel element instead of foil. These elements were annular, 15.24-mm o.d. by 6.35-mm i.d. and contained 49.00 g U(93.15) and 167.8 g carbon in each 762-mm length (two 381-mm sections taped together). Except for a shortened core, discussed later, a triangular pattern of the elements, on 22.86-mm centers, was established using two 1.6-mm-thick aluminum templates.

In the thin reflector, an annular pattern of elements like that shown in Fig. 9 was built up to 200 elements loaded and extrapolated to the critical number 207.0. For the two-dimensional model of Table XIV, the critical masses, 10143 g U(93.15) and 34735 g carbon, were spread uniformly between 48.0- and 179.2-mm radii.

TABLE XII

COORDINATES OF CRITICAL FOIL-LINER CORE IN THIN BERYLLIUM REFLECTOR

z (mm)	r (mm)	Material
441.32-441.72	0-190.50	859 g U(93.1)
441.72-1192.21	189.87-190.50	10695 g U(93.1)
1192.21-1193.80	0-190.50	6061 Al
1193.80-1194.01	0-190.50	451 g U(93.1)

TABLE XIII

COORDINATES OF CRITICAL FOIL-LINER CORE IN THICK BERYLLIUM REFLECTOR

z (mm)	r (mm)	Material
441.32-441.52	0-190.50	429 g U(93.1)
441.52-1192.21	190.05-190.50	7644 g U(93.1)
1192.21-1193.80	0-190.50	6061 Al
1193.80-1194.00	0-190.50	429 g U(93.1)

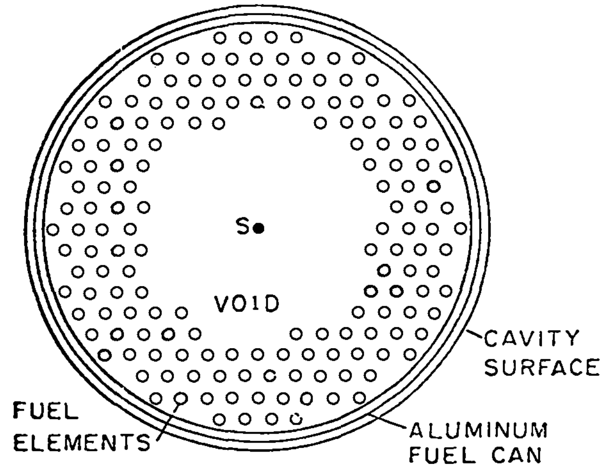

Fig. 9.
Annular distribution of Rover elements in beryllium assemblies. S represents the neutron source locations.

The other Rover fuel core in the thin reflector had the cavity shortened to about 381 mm by filling the lower portion with beryllium. In this case, 445 one-half-length close-packed elements nearly filled the cavity in the absence of templates. The extrapolated critical number, 454.1 (11 125 g uranium and 38 099 g carbon), was smeared over the entire cavity as described in Table XV.

Two other cores were of full-length Rover fuel in the thick beryllium reflector. Again, elements were positioned by the two aluminum templates. One, with the annular arrangement shown in Fig. 9, was built up to 160 elements, which extrapolated to the critical number 169.6. In Table XVI, the corresponding 8310 g U(93.15) and 28 459 g carbon are distributed between the 87.71- and 179.20-mm radii.

The final core consisted of elements clustered on the axis at the 22.86-mm center-to-center spacing defined by the templates. The extrapolated critical number of elements, 199.1 (195 actually stacked) contained 9756 g U(93.15) and 33409 g carbon. Table XVII gives the two-dimensional description of this material contained within a 169.4-mm radius.

Although the thin, uniform foil liner in the D_2O system provides a better two-dimensional model than the Rover fuel cores, the reverse may be true of the beryllium assemblies with their smaller cavities. Nonuniform layers of foil building beyond a mean-free-path for thermal neutrons are dubiously represented by the average thickness. On the other hand, the relatively high density of Rover elements in the beryllium-reflected cores tends to favor homogenization. For these reasons, the descriptions in Tables XIV-XVII are expected to be better than

TABLE XIV

COORDINATES OF CRITICAL ROVER FUEL ANNULUS IN THIN BERYLLIUM REFLECTOR

z (mm)	r (mm)	Material
441.32-593.72	48.00-179.20	2028.60 g U(93.15) and 6947 g C
593.72-595.31	0-48.00	Al(6061), 1.35 g/mℓ
593.72-595.31	48.00-179.20	21.13 g U(93.15), 72 g C, and Al(6061), 1.35 g/mℓ
593.72-595.31	179.20-190.50	Al(6061), 1.35 g/mℓ
595.31-1050.92	48.00-179.20	6064.67 g U(93.15) and 20769 g C
1050.92-1052.51	0-48.00	Al(6061), 1.35 g/mℓ
1050.92-1052.51	48.00-179.20	21.13 g U(93.15), 72 g C, and Al(6061), 1.35 g/mℓ
1050.92-1052.51	179.20-190.50	Al(6061), 1.35 g/mℓ
1052.51-1203.32	48.00-179.20	2007.47 g U(93.15) and 6875 g C

TABLE XV

COORDINATES OF CRITICAL ROVER FUEL FILLING SHORT CAVITY IN THIN REFLECTOR

z (mm)	r (mm)	Material
441.32-838.20	0-190.50	Be, 1.664 g/mℓ[a]
838.20-1219.20	0-190.50	11125.45 g U(93.15) and 38099 g C

[a]Because the weight of this beryllium was not recorded, its average density is approximate: the actual beryllium height was 406 mm and the closure plug was depressed ~10 mm to provide clearance for the 381-mm-high fuel.

TABLE XVI

COORDINATES OF CRITICAL ROVER FUEL ANNULUS IN THICK BERYLLIUM REFLECTOR

z (mm)	r (mm)	Material
441.32-593.72	87.71-179.20	1662.08 g U(93.15) and 5692 g C
593.72-595.31	0-87.71	Al (6061), 1.35 g/mℓ
593.72-595.31	87.71-179.20	17.31 g U(93.15), 59 g C, and Al (6061), 1.35 g/mℓ
593.72-595.31	179.20-190.50	Al (6061), 1.35 g/mℓ
595.31-1050.92	87.71-179.20	4968.93 g U(93.15) and 17 016 g C
1050.92-1052.51	0-87.71	Al (6061), 1.35 g/mℓ
1050.92-1052.51	87.71-179.20	17.31 g U(93.15), 59 g C, and Al (6061), 1.35 g/mℓ
1050.92-1052.51	179.20-190.50	Al (6061), 1.35 g/mℓ
1052.51-1203.32	87.71-179.20	1644.77 g U(93.15) and 5632 g C

those in Tables XII and XIII (beryllium-foil) but still not as reliable as the r,z representation of the D_2O-foil assembly.

REFERENCES

1. G. A. Jarvis and C. C. Byers, "Critical Mass Measurements for Various Fuel Configurations in the LASL D_2O Reflected Cavity Reactor," AIAA Paper No. 65-555, Colorado Springs, CO, June 1965.

2. C. B. Mills, "Reflector Moderated Reactors," Nucl. Sci. Eng. **13**, 301 (August 1962).

3. H. H. Helmick, G. A. Jarvis, J. S. Kendall, and T. S. Latham, "Preliminary Study of Plasma Nuclear Reactor Feasibility," Los Alamos Scientific Laboratory report LA-5679 (August 1974).

4. W. Bernard, H. H. Helmick, G. A. Jarvis, E. A. Plassmann, and R. H. White, "Research Program on Plasma Core Assembly," Los Alamos Scientific Laboratory report LA-5971-MS (May 1975).

TABLE XVII

COORDINATES OF CRITICAL ROVER FUEL CLUSTERED ON AXIS IN THICK BERYLLIUM REFLECTOR

z (mm)	r (mm)	Material
441.32-593.72	0-169.36	1951.18 g U(93.15) and 6682 g C
593.72-595.31	0-169.36	20.32 g U(93.15), 70 g C, and Al (6061), 1.35 g/m/
593.72-595.31	169.36-190.50	Al (6061), 1.35 g/m/
595.31-1050.92	0-169.36	5833.22 g U(93.15) and 19976 g C
1050.92-1052.51	0-169.36	20.32 g U(93.15), 70 g C, and Al (6061), 1.35 g/m/
1050.92-1052.51	169.36-190.50	Al (6061), 1.35 g/m/
1052.51-1203.32	0-169.36	1930.86 g U(93.15) and 6612 g C

5. S. A. Colgate and R. L. Aamodt, "Plasma Reactor Promises Direct Electric Power," Nucleonics **15**, No. 8, 50 (August 1957).

6. R. S. Cooper, Ed., "Proceedings of an Advanced Nuclear Propulsion Symposium," Los Alamos Scientific Laboratory report LA-3229-MS (June 1965).

7. J. F. Kunze, G. D. Pincock, and R. E. Hyland, "Cavity Reactor Critical Experiments," Nuclear Appl. **6**, 104 (February 1969).

☆ U.S. GOVERNMENT PRINTING OFFICE: 1975—677-343/3

8. J. F. Kunze, J. H. Lofthouse, C. G. Cooper, and R. E. Hyland, "Benchmark Gas Core Critical Experiment," Nucl. Sci. Eng. **47**, 59 (January 1972).

9. I. K. Kikoin, V. A. Dmitrievskii, Iu.Iu. Glazkov, I. S. Grigor'ev, B. G. Dubrovskii, and S. V. Kersnovskii, "Experimental Reactor with Gaseous Fissionable Substance," Sov. J. At. Energy **5**, 1167 (September 1958).

10. G. I. Bell, "Calculations of the Critical Mass of UF_6 as a Gaseous Core with Reflectors of D_2O, Be, and C," Los Alamos Scientific Laboratory report LA-1874 (February 1955).

11. G. Safonov, "The Criticality and Some Potentialities of Cavity Reactors," RAND Corporation research memorandum RM-1835 (July 1955).

12. R. E. Hyland, R. G. Ragsdale, and E. J. Gunn, "Two-Dimensional Criticality Calculations of Gaseous Core Cylindrical Cavity Reactors," NASA TN D-1575 (1963).

13. T. F. Plunkett, "Nuclear Analysis of Gaseous-Core Nuclear Rockets," Nuclear Appl. **3**, 179 (March 1967).

14. T. S. Latham, "Criticality Studies of a Nuclear Light Bulb Engine," AIAA Paper No. 68-571, Cleveland, OH, June 1968.